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On the Resilience of Systems of Systems

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***Abstract*—The need to consider how systems can be made resilient to failure modes has gained increasing traction in the fields of systems thinking and systems design, and is now more widely studied, with authors identifying the potential disruptive effects of failure upon a system, and codifying these disruptions into specific types. When the focus of specification moves from the bounded single system to the consideration of capability and effect, systems-of-systems, rather than systems must be contended with. Systems-of-systems have been classified as being of a number of types (acknowledged, collaborative, directed, virtual, for example), whilst authors have endeavoured to characterise the properties of systems-of-systems, and the difficulties associated with their design, introduction and operation. This study has invariably arrived at the conclusion that systems-of-systems are infinitely more complex than bounded single systems, and as the final system-of-systems design will still need to be resilient to failure, this in turn poses more difficult questions for the study of resilience, as the properties of a bounded single system are unlikely to be the same as those of a system-of-systems. This paper will consider the problems faced by the need to specify resilience in a system-of-systems environment, by first evaluating how the various types and properties of systems-of-systems might affect the consideration of resilience, and then proposes an initial codification of systems-of-systems resilience disruption types, along with recommendations and required further work.**

Keywords—systems; systems-of-systems; resilience; disruptions

I. Introduction

The move towards specifying, designing, and procuring ‘capability’ rather than constituent platforms over the past decade or so has led necessarily to the consideration of more complex and intricate systems and system requirements [1-3]. This in turn has caused academics and practitioners to focus on not just systems, but systems-of-systems. This shift has caused a number of issues when considering the problem: if we take, for example, definitions of the terms ‘system’ and ‘system-of-systems’ from the same source – Systems Engineering Book of Knowledge (SEBoK) [4] – then ‘system’ is defined as a “*combination of interacting elements organized to achieve one or more stated purposes”* [5], whilst ‘system-of-systems’ is defined as “*System-of-systems applies to a system-of-interest whose system elements are themselves systems; typically these entail large scale inter-disciplinary problems with multiple, heterogeneous, distributed systems”* [6]. It can be seen from these definitions that whilst a system is a bounded set of interacting elements focused on the attainment of a given outcome, then a system-of-systems is a combination of individual, holistic systems interacting in a particular way at a particular time. As such, it is reasonable to suggest that each individual system will exist to its own set of requirements, purpose, lifecycle, and have its own ownership and priorities. Combining such systems to achieve a particular outcome might thus necessarily bring different systems into conflict with each other. Thus the task of specifying, designing, managing and regulating such a large entity might be seen to be of a higher order of complexity and difficulty. This is even more so when engineering within the capability domain, as we may be considering not just a system-of-systems, but multiples thereof: *systems-of-systems*. How, for example, in a world ever-more obsessed with the mantra ‘faster, cheaper, better’ [7], are increasingly complex systems to be specified and designed [8] in an agile manner? [9]. Moreover, how can such complex systems-of-systems be made to operate reliably, and be as available and maintainable as is necessary across time? Whilst reliability is well defined in literature, for example “*Reliability is a characteristic of the item, expressed by the probability that it will perform its required function under given conditions for a stated time interval”* [10], the unpredictable and extended nature of systems-of-systems can prevent availability of knowledge required to calculate reliability. This lack of definitive calculations raises the topic of *resilience*, which can be defined as “*the ability of a system, process, or organisation to react to, survive, and recover from disruptions*” [11]. The very heterogeneity of systems-of-systems makes the question of resilience of great importance. To this end, there has been a growing interest in the topic of systems resilience [12], but until recently this has been focused at the systems- rather than system(s) of systems-level. There has been increasing focus on the problems associated with implementing system-of-systems [13-15], and also a move toward attempting to understand what resilience means for systems-of-systems [11, 16, 17]. However, this area of research remains relatively new, and what resilience means in a systems-of-systems environment is still an emerging topic. To this end, this paper attempts to understand the nature of types of disruptions to which systems-of-systems might need to be resilient, and then to propose an initial codification of systems-of-systems resilience disruption types. Recommendations and further work will then set out how these ideas might be taken forward.

II. SYSTEMS-OF-SYSTEMS DEFINITIONS

Before examining the nature of resilience and existing work on disruptions, it is useful to briefly define the concept of 'system-of-systems', to set out the challenges faced in codifying the nature of disruptions. There have been several definitions postulated, examples of which are described below:

"systems-of-interest whose system elements are themselves systems; typically these entail large-scale inter-disciplinary problems involving multiple, heterogeneous, distributed systems. These interoperating collections of component systems usually produce results unachievable by the individual systems alone" [18]

"An **SoS** is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities" [19]

"a system-of-systems is a super system comprised of elements that are themselves complex, independent systems which interact to achieve a common goal" [20]

"An organised collection of interacting systems" [21]

From these definitions we can identify certain characteristics of system-of-systems which are likely to render the specification of resilience more challenging. These might be summarised as described at Table 1.

TABLE 1: System-of-systems Characteristics

Characteristic	Observation
Emergent Behaviour	An SoS is capable of tasks that the individual systems cannot achieve. This emergent behaviour is not always predictable and can have positive or negative outcomes
Complexity	SoS have complex interactions and dependencies. These interactions will change depending on the SoS configuration
Independence	Each component system of an SoS has its own purpose, and can be used independently of the SoS
Geography	There is a tendency to geographical dispersion
Sub-optimalisation	Each element has not been designed with the SoS purpose in mind

These characteristics present issues for the engineering of system-of-systems, especially when compared to systems. Considerations for engineering and design of such factors have been documented [22-24] as at Table 2.

TABLE 2: Design and Engineering comparison between systems and System-of-Systems, taken from [22]

Boundaries and Interfaces	Focuses on boundaries and interfaces	Focus on identifying systems contributing to SoS objectives and enabling flow of data, control and functionality across the SoS while balancing needs of the systems OR focus on interactions between systems. Difficult to define system-of-interest
Performance and Behaviour	Performance of the system to meet performance objectives	Performance across the SoS that satisfies SoS use capability needs while balancing needs of the systems
Metrics	Well defined (e.g., INCOSE handbook [6])	Difficult to define, agree, and quantify

III. EXAMINING CLASSIFICATIONS OF SYSTEMS-OF-SYSTEMS

As a means to further understand system-of-systems in the light of difficulties in characterizing and specifying them, types of systems have also been examined [25, 23], and can be described as follows [15]:

"Directed - The SoS is created and managed to fulfil specific purposes and the constituent systems are subordinated to the SoS. The component systems maintain an ability to operate independently; however, their normal operational mode is subordinated to the central managed purpose.

Acknowledged - The SoS has recognised objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on cooperative agreements between the SoS and the system.

Collaborative - The component systems interact more or less voluntarily to fulfil agreed upon central purposes. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards.

Virtual - The SoS lacks a central management authority and a centrally agreed upon purpose for the system-of-systems. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely on relatively invisible mechanisms to maintain it."

This classification can usefully be employed in considering how resilience might be adapted to the systems-of-systems context.

IV. The Need for Resilience

A. *The Importance of Resilience*

Increasing complexity and interdependencies in systems-of-systems has increased the potential for disruptive events to interact with element(s) of the constituent systems within a system(s)-of-systems [26]. As a result, there are likely to exist more opportunities for disruptions to occur at system(s)-of-systems level of abstraction. Moreover, as system(s)-of-systems become more pervasive and critical, disruptions will generate more significant impacts:

- Loss of system function
- Negative emergent properties
- Safety implications

In relation to a disruptive event, a *system* will need to contain one or more of absorptive, adaptive, and restorative capacities [12]. However, a system's capacity for resilience is necessarily dependent upon both its boundary, and the nature of the effect that is being disruptive. Given the larger, more diverse and heterogeneous nature of system(s)-of-systems, the possibility of a disruptive episode at either system- or *supersystem*-level must therefore be greater.

B. *Existing Understanding of Resilience*

Disruptive events, described above, are the principal reason for requiring resilience. Without these events, there would be no need for resilience. A 'disruption' can be defined as: *an event or situation that interacts with the system of interest and has the potential to modify the system's emergent properties and measures of performance*. Such disruptions can be categorised as follows [12]:

- Type A: Disruptions of Input
- Type B: Systemic disruptions

In both cases, these disruptions can be predicted or unpredicted. Type A disruptions, as shown in Figure 1, are from outside the system, and tend to cause a loss of system function.

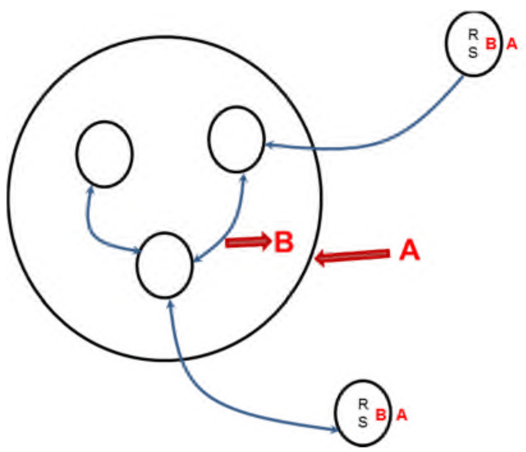

Figure 1: Notional system, sub-systems, and related systems with Type A and B disruptions indicated

These are environmentally driven, and can be some of the easiest disruptions to identify, especially those from the physical environment; examples might be:

- Natural disasters/ extreme weather
- Hostile military action

Knowledge of these Type A disruptions initially drives absorptive capacity requirements, such as survivability parameters of a platform system such as an armoured vehicle. There are 8 principal environments that can generate Type A disruptions [12]: Cultural, Political, Economic, Organisational, Regulatory, Geopolitical, Contractual, and Physical.

Type B disruptions, on the other hand, are disruptions that are systemically realized. They are internal to the system and originate in either system elements or emerge from interactions between two or more elements/ sub-systems. They are commonly, but not exclusively, reliability or safety failures [12]. As with the Type A family, Type B disruptions generate loss of function, capability or capacity and are classified by [12] as follows:

- Component Failure
- Systems Failure

Component Failures are the result of a failure of a system element/ subsystem (for example through unreliability), whereas the Systems Failure classification relates to the negative emergence from two or more elements interacting in some way, for example incorrectly applied management interventions or frictional wear through poor engineering design. They tend to be most evident in technological systems, as diagnosis is often simpler, although any system is capable of internally generating Type B disruptions.

V. Resilience in System(s)-of-Systems

System resilience is considered to be at the cutting edge of systems engineering research, and the topic continues to evolve quickly. Resilience for System(s)-of-Systems, given the sometimes opaque nature of the concept, is even less well-defined. As presented earlier, there is recent research into the area [11, 16, 17], especially within the systems safety and disaster management domains [27, 28], but as yet there are few defined rules or approaches.

If, however, we look at how resilient systems are treated, implications for applying the concept at the SoS level can be discerned. Given that resilience capacities described earlier are necessary in a system to combat disruptive events, a system-of-systems should similarly be expected to absorb, adapt, and/or recover from disruptions to exhibit resilience. However, not all system(s)-of-systems are intentionally designed or engineered. This raises two questions:

- How do we ensure the system(s)-of-systems is resilient?
- Can we ensure that it continues to be resilient?

This could be seen to depend on the type of system(s)-of-systems. An illustration of this [26] is provided at Figure 2. An additional type, that of *accidental,* has been added to account for the possibility of involuntary, or chance, system(s)-of-systems occurrences.

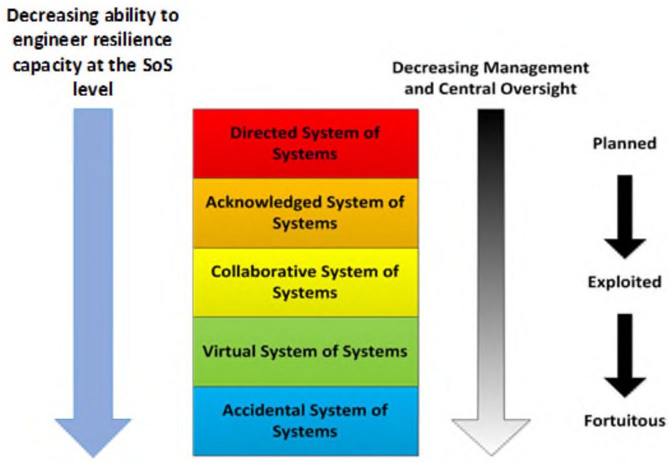

Figure 2: Ability to engineer resilient capacity within system(s)-of-systems [26]

As can be seen from Figure 2, the ability to successfully engineer resilience into a system(s)-of-systems decreases as the type of system(s)-of-systems becomes less well-regulated, and more loosely configured. So, for example, a *directed* system(s)-of-systems, created to fulfil a specific purpose, and centrally managed and coordinated to that end, is definable, and therefore potentially quantifiable in terms of the necessary resilience required to combat any disruptive event(s). This might also be true, although to a slightly lesser extent, for an *acknowledged* system(s)-of-systems, with its recognised objectives, designated manager, and resources. However, a collaborative system(s)-of-systems, relying upon voluntary agreements to function, is likely to be much more challenging to define in terms of required resilience, and by the time we get to *virtual* and *accidental* system(s)-of-systems, the emergent nature of component systems and interrelationships between them would render a quantification of resilience continuous and ever-changing.

VI. CODIFYING DISRUPTIONS FOR SYSTEM(S)-OF-SYSTEMS

In considering the nature of disruptions, and the dynamic and detailed complexity exhibited by different types of system(s)-of-systems, it is reasonable to suggest that whilst the component systems themselves may be resilient, the act of bringing them together in a new system(s)-of-systems-architecture greatly increases the chance of disruptions generated through the relationships/ interconnection between the systems. Given the fundamental nature of system-of-systems being comprised of independent systems, any engineered resilience at this level only focuses on the continuation of delivering its own system function during times of disruption. Consequently, any action taken will be done in isolation of the other constituent systems, meaning that decisions are not likely to be optimised for the system-of-systems as a whole, leading to conflicting actions at either end of a relationship/ interconnection between systems, raising the potential for the generation of disruptions at this point of the system-of-systems.

Whilst there is scope, at the Directed- and Acknowledged-system-of systems levels, for the single point of managerial control/ oversight to optimise and guide how the constituent systems respond to disruptions, this is not an option for Collaborative and Virtual Systems-of-Systems. This is due to the lack of a single individual holding the role of management authority for these system-of-systems types.

This lack of control has implications for the codification of disruption types at the system-of-systems level, since control and ownership now become important factors in being able to respond to disruptions. The expansion of the system-of-systems boundary from the collection of constituent system boundaries means that it is exposed to a wider array of potential environments from which disruptions can originate. Applying this to the Type A disruptions means that at the system-of-systems level, two distinct variations of Type A disruption sources manifest:

- Those that are external to a system boundary, apply to a system, but may originate from within the System-of-Systems Boundary;
- Those that are external to the system-of-system boundary, and apply to the system-of-systems as an entity.

The first of these situations would, from the perspective of a system owner, remain a Type A disruption given it is a disruption of input to their system. However, from the wider system-of-systems perspective, it cannot be considered a Type A disruption as it originates within the SoS boundary, meaning it is not a disruption of input to the SoS. Given it does not emerge from the internal systems or their interconnections; this disruption is also not of the Type B class. In effect it lies somewhere in between, and is able to evolve depending upon the level of systemic hierarchy used as the observation. It is therefore proposed by the authors that such disruptions are a new and previously unexamined type, unique to system-of-systems that have no central management oversight. We label these Type C disruptions, and call them 'Internal Environment Disruptions'.

The second of the situations highlighted above would also be perceived as a Type A disruption at the system level due to its origination from outside of the system boundary. As it also originates from outside the SoS boundary, it remains a Type A disruption when also viewed from the SoS perspective. However, the constituent environments that comprise these disruption types are likely to be more strategic in nature, given their wide ranging influence on the entire system-of-systems. This is especially true once the geographically dispersed nature of SoS, as highlighted in Table 1, is considered. Therefore, whilst these disruptions mimic the 8 system-level Type A environments from [12], they are likely to have a more limited number of disruptions that arise from each environment due to their system-of-systems level influence. We therefore consider that whilst such disruptions remain Type A, they are a variant of those found at the systems level. We therefore refer to them as Type A^1 disruptions, which are applicable only to Collaborative and Virtual system-of-systems. We call these 'Strategic Disruptions of Input'. An example of such a Type A^1 disruption would be a change in the Rules of Engagement for a joint coalition military operation comprising several countries and many different types of units.

As with the exploration of applying the system level Type A disruption approach to collaborative systems-of-systems, we have also examined how Type B disruptions apply when considered within these entities.

As Type B disruptions at the system level are disruptions generated by either component/ subsystem or system failure, when the concept is applied to the system-of-systems level, it remains valid, except the approach considers systems and inter-system failures. As such, it suggests a hierarchical consideration of Type B disruptions could be one way of treating these disruption types at the system-of-systems-level. This means that the system- and systems-of-systems-level Type B disruptions are essentially identical in terms of concept and content. However, as with our examination of Type A disruptions, the issue of system control and likely generation source of the Type B disruptions at the different hierarchical levels are the consideration in how they are codified. To distinguish between those at the systems level and those at the system-of-systems level, we label those system-of-systems systemic disruptions as Type D disruptions and call them 'Disruptions of Emergence.'

An illustration of the four disruption types in relation to the notional system from Figure 1 and wider system-of-system boundary is shown by Figure 3, and expanded by Table 3.

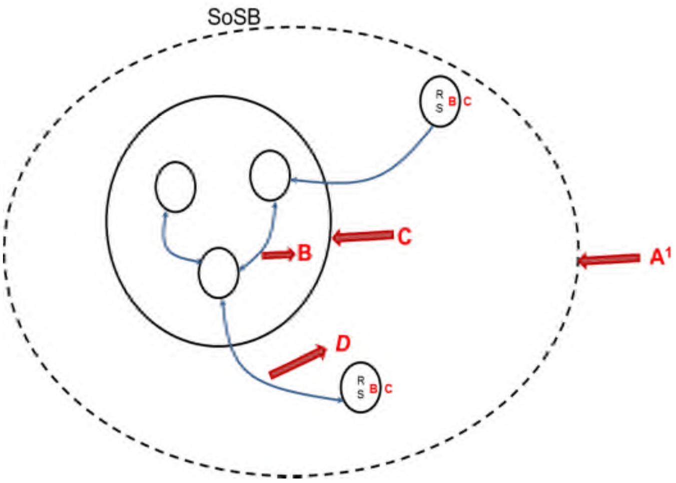

Figure 3: Notional system from Figure 1, with system-of-systems boundary and suggested additional types of disruption

TABLE 3: System-of-systems Disruption Types

Disruption Type and Name	Description	Examples
A^1 – Strategic Disruption of Input	Disruptions that originate outside the SoS boundary and impacts all constituent systems within the SoS.	1. Funding shortfall for whole SoS 2. Rules of Engagement change for a coalition operation
B – Systemic Disruptions	'Local' disruption that originates within a constituent system. Two sources: 1. Failure of a system element/ subsystem 2. Failure from negative emergence from two or more interacting elements	1. Unreliable component within constituent system 2. Incorrect use of constituent system from poorly trained operator
C – Internal Environmental Disruption	'Local' disruption that originates inside the SoS boundary but outside constituent system boundaries. Impacts one or more constituent systems.	1. Funding shortfall for a constituent system 2. Enemy attack on single constituent system
D – Disruption of Emergence	Disruption generated by negative emergence from the interaction of two or more constituent systems within the SoS.	1. Sensor interference within a Coalition Task Group 2. Language difficulties between constituent systems

VII. Conclusions and Recommendations

From our research conducted so far, we have found that the unique nature and challenges of collaborative systems-of-systems prevents optimal application of many of the accepted and, often basic assertions, associated with resilience engineering. Simple resilience concepts, whilst applicable to systems-of-systems generically, begin to become nebulous when faced with challenges over control and ownership. This is an important consideration that must be factored into future exploration of the nature of resilient systems-of-systems as assumptions, whilst appropriate for systems and the more tightly controlled systems-of-systems that are categorised as directed or acknowledged, fail to comprehensively describe or apply to the less centralised collaborative and virtual systems-of-systems.

In this paper we have considered the nature and codification of disruption types when considered and applied at the systems-of-systems level. We start with those disruption types presented within [12] for application at a system level, and propose an extension of this codification for application at the systems-of-systems level, specifically focusing on those systems-of-systems that exhibit no single point of management oversight or control (i.e. collaborative and virtual systems-of-systems). In doing so we propose the requirement for an evolution of the existing Type A disruptions into those that are more ‘strategic’ in nature – the Type A^1 disruptions. Two new types of disruption – Type C and Type D – are proposed to fill the gaps in disruption sources for complex systems-of-systems that are not filled by either current Type A and Type B families.

Whilst originating from the same consideration of Type A disruptions upon the system-of-system environment, differences between the Type A^1 and Type C disruption types are likely to be more marked given their relative positioning across the system-of-systems. Type A^1 disruptions are a subset of Type A disruptions specifically codified to demonstrate the strategic nature of the disruption. Type C however represents something new and is unique to the less centralised system-of-systems environments found in their collaborative and virtual subtypes. Whilst undoubtedly related to the system level Type A (and system-of-systems Type A^1), the main differentiator is the positing and ability to influence the disruption source. As it is within the system-of-systems boundary, it suggests that the system-of-systems owner can control the imposition of Type C disruptions. Whilst this may be true for Directed Systems-of-Systems, it is unlikely to be so for the looser/ unmanaged types we specifically consider in this research. It is therefore postulated that such disruptions may remain unknown or uncontrollable until they manifest themselves with observable impacts upon system/ system-of-system functional output.

Stemming from the same consideration of Type B disruptions upon the system-of-systems environment, Type B and Type D disruptions are closely related to each other, merely representing similar consideration of systemic disruptions but at different levels of the systemic hierarchy. Indeed, at the more tightly controlled types of systems-of-systems, it is expected that they will coalesce into a single family type as control and direct management extends across the systems within the system-of-systems. For collaborative/ virtual systems-of-systems we suggest they will only differ in composition due to the emergent nature of properties found as complexity and dynamism increases at the higher systemic levels. In practice, we expect to see disruptions transition between the two types (in either direction) depending upon system composition, their states and how they evolve through use over time. It is highly likely that Type B disruptions will create Type D disruptions and vice versa as they perturbate along intra-system relationships.

The consideration of system-of-system resilience disruptions and the proposed new disruption types has been conducted from an initial theoretical perspective and at mainly a high level considering the behavioural nature of systems-of-systems as the foundation for our investigations. To this end, an iterative process of applying our proposed disruption types to a case study will provide interesting and useful information to refine the concept, including identification of common Type A^1 and Type D disruptions. Such an exercise will enable us to examine the evolutionary nature of the disruption types, with the potential for modelling the transition between types as a system state evolves through use. This will be of significant applicability to those practitioners and users who focus on availability, reliability and maintainability properties of systems, for example within the defence sector.

Further investigation and development of Type C disruptions to examine the possibility of deriving heuristics or common categories of disruption will prove useful, as will understanding how decision making within the context of control and management limits can modify or mitigate these disruptions. However, whether it is possible to directly influence and mitigate Type C disruptions within collaborative system-of-systems (given the real world lack of oversight/ control that is difficult to replicate within an observable model/ case study) remains to be seen.

Finally, we hypothesise that it may be possible, through the observation of deleterious effects on functional output (and thus on performance) as they manifest themselves within a system context, to yield increased knowledge and information about the interconnections and relationships between the system of interest and those around it. This means that a system level observer, who is unaware that their system may be in a system-of-systems, may obtain sufficient knowledge to elevate themselves to a system-of-systems level observer with knowledge and oversight of other related systems. In doing so, it is theorised that this may enable a virtual system-of-systems to transition to a collaborative one.

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